DURABILITY of CONCRETE STRUCTURES

PART 2

Prof. Dr. Halit YAZICI
PHYSICAL & MECHANICAL FACTORS

CAUSES of MASS LOSS
- WEARING, EROSION, CAVITATION
- FREEZE-THAW, DE-ICING AGENTS, WETTING & DRYING, CHANGE of LENGTH & VOLUME

CAUSES of CRACKS
- FIRE, HIGH TEMPERATURES
- EXCESSIVE LOADING, REPEATED LOADING, FATIGUE LOADING, IMPACT LOADS
WEARING, EROSION, CAVITATION

- **Dry Friction Effect**
  - Traffic Load (Tanks & Loaders, etc.)
  - Drag of Heavy Materials
  - Abrasive Wearing
  - Mass Loss Within Time

- **Wearing of Concrete Surfaces** by Liquids with Suspended Solids
  - Erosion

- **Flow of Water with High Velocity**

- **Sudden Drops of Pressure**, **Impact of Water Bubbles on Surface**

- **Cavitation**
WEARING, EROSION, CAVITATION

WEAK SURFACE DUE TO HIGH W/C

EXCESSIVE TROWELLING
CAVITATION HAZARDS on a SPILLWAY of a DAM
Cavitation damage to the concrete wall of the 15.2m diameter Arizona spillway at the Hoover Dam. The hole is 35m long, 9m wide and 13.7m deep.
WEARING, EROSION, CAVITATION

CRASHING of VEHICLES
WEARING, EROSION, CAVITATION

CONCRETE SURFACE WEARED by STUDDED TIRES

CONCRETE SURFACE AFTER WEARING TEST
WEARING, EROSION, CAVITATION
PROPER GRADATION

APPROPRIATE COMPACTION

LOW W/C RATIO

BETTER CURING

PROPER SURFACE FINISHING

USING SURFACE HARDENERS  CAUTION: ASR

SOME of THESE METHODS MAY BE IMPLEMENTED TOGETHER
EFFECTIVE MEASURES in CONTROLLING WEARING, EROSION, CAVITATION

Siliceous powder poured on slab should contain no reactive silica

Expansion & pop-out
# Classification of Environmental Exposure – TS EN206

<table>
<thead>
<tr>
<th>WEARING</th>
<th>XM1</th>
<th>XM2</th>
<th>XM3</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAX. W/C RATIO</td>
<td>0.55</td>
<td>0.55-0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>MIN. STRENGTH</td>
<td>C30/37</td>
<td>C30/37-C35/45</td>
<td>C35/45</td>
</tr>
<tr>
<td>MIN. DOSAGE kg/m³</td>
<td>300</td>
<td>300-320</td>
<td>320</td>
</tr>
</tbody>
</table>

**XM1**
- **Moderate Wearing Effect**
  - Floors subjected to plastic-wheeled traffic or industrial floors with surface hardeners

**XM2**
- **Excessive Wearing Effect**
  - Floors subjected to plastic-wheeled or rubber tyred traffic, industrial floors with surface hardeners

**XM3**
- **Very Excessive Wearing Effect**
  - Floors subjected to steel or elastomer tyre-wheeled traffic and impact, frequently use of tyre-chains, industrial floors with surface hardeners, water structures vulnerable to erosion
FREEZE & THAW EFFECT

**FRESH CONCRETE**
- RETARDATION or DELAY of HYDRATION REACTION (<-12°C)
- FORMATION of PORES by SWELLING EFFECT of ICE
- RE-INITIATION of HYDRATION by MELTING of ICE
- VERY POROUS STRUCTURE, DECREASE of DURABILITY & MECHANICAL PROPERTIES
- NECESSITY of REMIXING FRESH-THAWED CONCRETE !!

**HARDBENED CONCRETE**
- FREEZING of CAPILLARY WATER
- SWELLING (~9%)
- INTERNAL STRESSES
- CRACKS
- DAMAGE
FREEZE & THAW EFFECT

FROZEN CONCRETE AT FRESH STATE
FREEZE & THAW EFFECT

3 FACTORS AFFECTING FREEZE-THAW RESISTANCE of CONCRETE:

- PORE STRUCTURE
- SATURATION of CONCRETE
- COMPRESSIVE STRENGTH (SUGGESTED VALUES 5-14 MPa !!!!!)

INTERESTING CONTRAST

TOO MUCH PORES (HONEY COMBED)
IMPERMEABLE
DRY CONCRETES

NOT AFFECTED by FREEZE&THAW!
PRECAUTIONS

SUPPLIER’S PRECAUTIONS

- TO PLACE CONCRETE AT WARMER PERIOD of DAY
- TO PRODUCE HIGH EARLY STRENGTH CONCRETE
  a) TO USE a CEMENT WITH HIGH HYDRATION HEAT VALUE (FINE CEMENTS)
  b) HIGHER CEMENT CONTENT, LOWER W/C RATIO
  c) TO USE ACCELERATOR TYPE (ANTI FREEZING) ADMIXTURES (CaCl₂ CONTENT MAX 1%)
  d) STEAM CURING
  e) IMPLEMENTATION OF VARIOUS METHODS SIMULTANEOUSLY

CONSUMER’S PRECAUTIONS
FREEZE & THAW HAZARD

Pop-outs due to insufficient aggregate usage (non-resistant to freezing&thawing)

Local pop-outs, Peelings, micro cracks in cement mortar matrix
FREEZE – THAW EFFECT
FREEZE – THAW EFFECT
FREEZE – THAW EFFECT

UŞAK-EŞME
FREEZE – THAW EFFECT

DENİZLİ, ÇAMELİ
REINFORCED RETAINING WALL
FREEZE – THAW EFFECT

DENİZLİ, AKDERE
REINFORCED GARDEN WALL
FREEZE – THAW EFFECT

DENİZLİ, IŞIKLI
REINFORCED CONCRETE SLAB
FREEZE – THAW EFFECT
PRECAUTIONS

- TO PRODUCE AIR ENTRAINED CONCRETE

AIR-ENTRAINING AGENTS
(SODIUM ABIETATE, LIGNO SULFONATE, VEGETABLE OILS,
SYNTHETIC DETERGENTS)

AIR BUBBLES 10-250 µ DIAMETER

AIR BUBBLES $3 \times 10^9$ ~ $7 \times 10^9$/m³  
2-9% of TOTAL VOLUME
PRECAUTIONS

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FREEZE & THAW HAZARD

Number of freezing-thawing cycles that causes 25% of weight loss

Air-entrained concrete

Non-air entrained concrete

W/C ratio

0.35 0.45 0.55 0.65 0.75 0.85

0 1000 2000 3000 4000 5000 6000 7000

FREEZE & THAW HAZARD
AIR ENTRAINING AGENTS

AFTER 140 FREEZE-THAW CYCLES

CEMENT DOSAGE
350 kg/m³

Entrained air

%4.6

%8.3

No strength loss in air entrained concrete
AIR ENTRAINING AGENTS

FREEZE-THAW CYCLES
## Suggested air entrainment percentages

<table>
<thead>
<tr>
<th>Maximum aggregate diameter (mm)</th>
<th>Total air content of concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>(Seldom effect of humidity &amp; de-icing agents)</td>
</tr>
<tr>
<td>9.5</td>
<td>6</td>
</tr>
<tr>
<td>12.5</td>
<td>5.5</td>
</tr>
<tr>
<td>19</td>
<td>5</td>
</tr>
<tr>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>37.5</td>
<td>5</td>
</tr>
</tbody>
</table>

### Fresh concrete
- Aerometer

### Hardened concrete
- Air void analyser
Variation of freezing point of water by pore diameter

Freezing Point (°C)

Saline water

Plain water

Pore radius (nm)

micro | mesa | macro
DE-ICING OPERATION
DE-ICING OPERATION LOWERS THE FREEZING POINT of WATER

DURING THAWING of ICE;
THERE WILL BE SUBSTANTIAL DROP in TEMPERATURE at THE CONCRETE SURFACE (THERMAL SHOCK)

TEMPERATURE DIFFERENCE BETWEEN SURFACE & INTERIOR of CONCRETE WILL CAUSE INTERNAL STRESSES
DE-ICING OPERATION CHANGE THE FREEZING BEHAVIOUR of PORE WATER

AS EXPLAINED BEFORE;
FREEZING POINT of PORE WATER WILL BE LOWER WHEN THE PORE RADIUS IS SMALLER.

AND ALSO;
THE CONTENT of DE-ICING AGENTS WILL DECREASE with INCREASING DISTANCE FROM THE SURFACE & with the DECREASING PORE RADIUS

BOTH THE CHANGE in CONTENT of DE-ICING AGENTS & CHANGE in TEMPERATURE, MAY CAUSE FREEZING at DIFFERENT TIME PERIODS FOR VARIOUS DEPTHS of CONCRETE LAYERS.

SCALING MAY OCCUR
EFFECTS of DE-ICING OPERATION

IN CASE of CHLORIDES;

(THE DE-ICING SALTS MOST FREQUENTLY APPLIED)

THERE IS A SERIOUS RISK of

REINFORCEMENT CORROSION
This picture is an illustration of a property owner that struggled with snow removal over the last two winters. Two visible snow lines can be seen on the sidewalk. The area on the left scaled where snow was stored for a long period at the sidewalk transition away from the roadway. And, the area on the right scaled where the snow was left in place due to the large volume that needed to be moved because of the snow plows.
## Classification of Environmental Exposure – TS EN206

### Freeze-Thaw Effect

<table>
<thead>
<tr>
<th></th>
<th>XF1</th>
<th>XF2</th>
<th>XF3</th>
<th>XF4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. W/C</td>
<td>0.60</td>
<td>0.55-0.50</td>
<td>0.55-0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Min. CEMENT DOSAGE (kg/m³)</td>
<td>280</td>
<td>300-320</td>
<td>300-320</td>
<td>320</td>
</tr>
<tr>
<td>Min. Entrained Air (%) (for D_max=32mm)</td>
<td>---</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

**OTHER**

FREEZE-THAW RESISTANT AGGREGATE

**XF1**: Moderately Water Saturated (Vertical Concrete Surfaces)

**XF2**: Moderately Water Saturated, De-Icing Agents (Vertical Concrete Surfaces)

**XF3**: Highly Water Saturated (Horizontal Concrete Surfaces)

**XF4**: Highly Water Saturated, De-Icing Agents (Horizontal Concrete Surfaces)
WETTING & DRYING

D CRACKS

JOINT INTERSECTIONS
CRACKING DUE TO COMBINATION of wetting&drying and freezing&thawing
HIGH TEMPERATURES
HIGH TEMPERATURES
<table>
<thead>
<tr>
<th>Temperature Range</th>
<th>Phenomenon</th>
</tr>
</thead>
<tbody>
<tr>
<td>100~150°C</td>
<td><strong>EVAPORATION</strong> of CAPILLARY WATER</td>
</tr>
<tr>
<td></td>
<td><strong>SHRINKAGE, FORMATION</strong> of MICRO CRACKS, <strong>DECREASE</strong> of TENSILE STRENGTH</td>
</tr>
<tr>
<td></td>
<td>– <strong>PINKISH COLOR</strong></td>
</tr>
<tr>
<td>150~200°C</td>
<td><strong>LOSS of HYDRATED WATER</strong> in AL.&amp;FERROUS COMPOUNDS, <strong>DECREASE</strong> of COMPRESSIVE STRENGTH – <strong>DEEP PINK</strong> – <strong>REDDISH COLOR</strong></td>
</tr>
<tr>
<td>~300°C</td>
<td><strong>Ca(OH)₂ → CaO</strong></td>
</tr>
<tr>
<td></td>
<td>30% <strong>VOLUME LOSS</strong></td>
</tr>
<tr>
<td></td>
<td>(DURING FIRE FIGHTING OPERATIONS)</td>
</tr>
<tr>
<td>400~600°C</td>
<td><strong>DESTRUCTION</strong> of CSH STRUCTURE</td>
</tr>
<tr>
<td></td>
<td>– GREY - <strong>WHITE COLOR</strong></td>
</tr>
<tr>
<td></td>
<td>~60-80% <strong>of COMPRESSIVE STRENGTH LOSS</strong></td>
</tr>
</tbody>
</table>
Loss of strength vs temperature for slow cooling and cooling by water.

- **Slow cooling**
- **Cooling by water**

**Temperature (°C)**

- 20
- 100
- 200
- 300
- 400

**Residual Strength (%)**

- 0
- 20
- 40
- 60
- 80
- 100
- 120
LOSS of STRENGTH

Residual Strength (%) vs. Temperature (°C)

- Limestone
- Gravel
- Color change
  - Pink or reddish
  - Gray
  - Ash

Temperature range:
- 20 to 1000 °C

Residual Strength range:
- 0 to 120%
HIGH TEMPERATURE RESISTANT MORTAR

Aggregate: Pumice
W/C ratio: 0.72
Air cooling

No strength loss at 900 °C

Residual compressive strength, %

![Graph showing residual compressive strength at different temperatures (300 °C, 600 °C, 900 °C). The graph indicates that there is no significant strength loss up to 900 °C.](image_url)
Figure 4.1 Portland cement and calcium aluminate cement concrete cylinders after 8 cycles of 6 hours at 500°C, followed by 24 hours in humid conditions.
Change of $\sigma$-$\varepsilon$ behaviour of structural steel due to high temp.

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td>99</td>
<td>2</td>
</tr>
<tr>
<td>149</td>
<td>3</td>
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<tr>
<td>204</td>
<td>4</td>
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<td>260</td>
<td>5</td>
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<tr>
<td>316</td>
<td>6</td>
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<tr>
<td>368</td>
<td>7</td>
</tr>
<tr>
<td>427</td>
<td>8</td>
</tr>
<tr>
<td>482</td>
<td>9</td>
</tr>
<tr>
<td>535</td>
<td>10</td>
</tr>
<tr>
<td>593</td>
<td>11</td>
</tr>
<tr>
<td>649</td>
<td>12</td>
</tr>
</tbody>
</table>
Precautions

Use mineral admixtures (fly ash, granulated blast furnace slag) Not silica fume

Use thermally stable aggregate

( limonite, basalt, barite, broken heat resistant bricks, korondonen, cromite etc.)

Use reinforcement with sufficient concrete cover (min. 4 cm for good fire resistance)
CHEMICAL & BIOLOGICAL FACTORS

I. GROUP
HYDROLYSIS, WASHING OUT

II. GROUP
IONIZATION REACTIONS WITH AGGRESSIVE CHEMICALS

III. GROUP
PRODUCTS of REACTIONS of EXPANSIVE NATURE

- SULFATE ATTACK
- DEF
- THAUMASITE FORMATION
- ASR, ACR
- DELAYED REACTIONS of CaO & MgO
- CORROSION of REINFORCEMENT

REMOVAL of Ca++ IONS by FORMATION of SOLUBLE or UNSOLUBLE PRODUCTS

REPLACEMENT of Ca++ IONS with Mg++ in CSH
HYDROLYSIS & WASHING OUT

\[ \text{pH} \approx 12.5 - 13.5 \]

CH

CSH

CAH

are STABLE
HYDROLYSIS & WASHING OUT

WATER WITH LOW pH (pH<6.5)

pH

DROPS

CH, CSH, CAH are NOT STABLE
HYDROLYSIS & WASHING OUT

CH, CSH, CAH

HYDROLYSIS

WASHED OUT
SOURCES OF LOW pH

WATERS WITH LOW pH

- INDUSTRIAL WASTE WATER
- SEA WATER
- UNDERGROUND WATER CONTAINING SULFATE &/or CHLORIDE
- WATER CONTAINING FREE CO$_2$ &/or H$^+$

DANGER LIMITS

MILD  pH = 5.5 - 4.5
SEVERE pH = 4.5 - 0.0

CONCRETE STRENGTH DECREASES 2%

with HYDROLYSIS & WASHING OUT of
1% Ca(OH)$_2$ (Mehta, 1997)
ACID ATTACK

Acid Solution from the environment

Conversion of hardened cement layer by layer: microstructure (pore system) destroyed

Converted layer; if not removed, more permeable than sound concrete

Removal of reaction products by dissolution or abrasion
ACID ATTACK

DISSOLUTION EFFECT OF WATER WITH pH<6.5 ON CEMENT MORTAR & CARBONATE AGGREGATES

STRONG ACIDS
SULFURIC ACID $\text{H}_2\text{SO}_4$
HYDROCHLORIC ACID $\text{HCl}$
NITRIC ACID $\text{HNO}_3$

WEAK ACIDS
$\text{H}_2\text{S} + \text{WATER FILM} + \text{OXYGEN} \rightarrow \text{H}_2\text{SO}_4$
$\text{SO}_3 + \text{WATER FILM} + \text{OXYGEN} \rightarrow \text{H}_2\text{SO}_4$
ACID ATTACK

From air

\[ \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3 \] (CARBONIC ACID)

\[ \text{CaO} + \text{CO}_2 \rightarrow \text{CaCO}_3 \] (MINERAL WATER)

\[ \text{H}_2\text{CO}_3 + \text{CaCO}_3 \rightarrow \text{Ca(HCO}_3)_2 \] (CALCIUM BICARBONATE)

\[ \text{Ca(HCO}_3)_2 + \text{Ca(OH)}_2 \rightarrow \text{CaCO}_3 + 2 \text{H}_2\text{O} \]

IF AMOUNT OF CO\textsubscript{2} IS LIMITED, THE REACTION WILL STOP AFTER A WHILE
INDUSTRIAL MATERIAL & WASTES and POLLUTED WATER MAY CONTAIN ORGANIC & INORGANIC COMPOUNDS.

FERTILIZER PLANTS WASTES
(FROM AMMONIUM NITRATE FERTILIZATION)

2NH₄NO₃ + Ca(OH)₂ + 2H₂O → 3Ca(NO₃)₂·4H₂O + 2NH₃

3Ca(NO₃)₂·4H₂O + 3CaO·Al₂O₃·6H₂O → 3CaO·Al₂O₃·Ca(NO₃)₂·10H₂O

SEWAGE WATER

H₂S + 2O₂ → H₂SO₄

Aerobic bacteria